Effects of Kaolin-Based Particle Film Application on Boll Weevil (Coleoptera: Curculionidae) Injury to Cotton

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ABSTRACT This study examined a non-insecticidal tactic for suppressing boll weevil, *Anthonomus grandis grandis* Boheman, damage to cotton, *Gossypium hirsutum* L. In cage assays, kaolin, a reflective white mineral, applied to excised cotton squares or to the cotton foliage, initially resulted in lower levels of boll weevil injury to squares than nontreated squares. Boll weevil oviposition and feeding on kaolin-treated squares and squares on kaolin-treated cotton plants increased when nontreated squares and cotton plants were in short supply. A laboratory assay and field trials suggested that boll weevils distinguished between cotton plots based on color differences caused by kaolin and this appeared to influence levels of damage to squares. Random sampling in small plots indicated that oviposition damage to squares in plots treated with kaolin was reduced ($P < 0.05$) compared with nontreated controls, except when rain washed the kaolin off the foliage. Lint yield differences were not detected between the small plots, but the kaolin-treated small plots yielded as much as 2.36 times more cotton lint than a large but unreplicated adjacent nontreated control plot, and up to 1.39 times more than another large but unreplicated adjacent plot sprayed twice with preemptive applications of azinphosmethyl when cotton squares were first developing (pinhead stage). Potentially important avenues for future research on boll weevil injury suppression using kaolin are discussed.

KEY WORDS boll weevil, *Anthonomus grandis grandis*, cotton, kaolin, particle film

INSECT AND DISEASE injury to some crops can be reduced by coating plants with kaolin as a particle film (Glenn et al. 1999). The film makes the host plant visually or tactually unrecognizable, and arthropod movement and feeding might also be hindered by the attachment of particles to the body. Kaolin is a white, porous, nonswelling, non-abrasive fine grained platy aluminosilicate mineral [$Al_4Si_4O_{10}(OH)_8$] that disperses in water and is chemically inert over a wide pH range. Coating grade kaolin is >90% pure and has a brightness quality of >85% (Harben 1995). Application of kaolin particle film has resulted in the suppression of injury caused by pear psylla, *Cacopsylla pyricola* Foerster, on pear; spirea aphid, *Aphis spireacola* Patch, potato leafhopper, *Empoasca fabae* (Harris), obliquebanded leafroller, *Choristoneura rosaceana* (Harris), and twospotted spider mite, *Tetranychus urticae* Koch, on apple; codling moth, *Cydia pomonella* (L.), on apple and pear (Glenn et al. 1999, Knight et al. 2000, Puterka et al. 2000, Unruh et al. 2000); and *Diaprepes* root weevil, *Diaprepes abbreviatus* (L.), on citrus (Lapointe 2000).

During the cotton, *Gossypium hirsutum* L., growing season, most commercial cotton growers rely on insecticides applied from squaring to cut-out to protect against crop losses caused by the boll weevil, *Anthonomus grandis grandis* Boheman (Loera-Gallardo et al. 1997, Page et al. 1999). Predators (Sterling 1978, Sturm et al. 1990), parasites (Morales-Ramos and King 1991; Summy et al. 1997a, 1997b), trap crops (Moore and Watson 1990), and plant extracts (Miles et al. 1993, 1994) have not been shown to control boll weevil populations in commercial cotton. Preliminary data suggested that kaolin had a deterrent effect on boll weevil oviposition on cotton (Showler 2001). Showler (2002) examined selected foliar free amino acid indicators for water-deficit stress (free proline) and for light reduction (free arginine) and found that kaolin coverage did not influence water potential, light reception, growth, and yield. This study was undertaken to examine effects of kaolin particle film on boll weevil oviposition and feeding damage to cotton squares.

Materials and Methods

The kaolin-based particle film used in this study was Surround wettable powder (Engelhard, Iselin, NJ), hereafter referred to as kaolin, processed to a bright white color of >85%, ≤2 μm particle diameter, and coated with a proprietary synthetic hydrocarbon. Sixty grams of kaolin per liter of water was used throughout this study. All applications, whether by painting, dipping, or spraying (in the laboratory, cages, and field plots), were done twice to ensure

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complete coverage. Reference to "7-mm square diameter stage" cotton plants hereafter means that at least five squares on the cotton plant were 7 mm in diameter and before bloom had commenced.

To quantify kaolin particle retention at 4 h and 4 d after application in 1 by 0.65 by 1-m screen cages in the laboratory, leaves on greenhouse-grown cotton plants in 7.5-liter pots were treated with a manual Greenlawn (Gilmour, Somerset, PA) 3.8-liter capacity pump sprayer with the nozzle adjusted to a cone spray pattern at a pressure of 2.7 kg/cm^2. Twenty randomly selected fully expanded leaves were excised after 4 h, and again after 4 d. The kaolin was washed from the leaves with methanol into preweighed plastic dishes (a 6-mm flat ox hair paint brush was used to dislodge particles that adhered to the leaf surfaces), the methanol was evaporated, and the dried particles plus the plastic dish were weighed. The difference between initial and final weights yielded the mass of kaolin on each leaf. The upper surface area of each leaf was measured using a model 3100 Area Meter (Li-Cor, Lincoln, NB). Total leaf surface area was estimated as two times the upper leaf surface area. The mass of kaolin collected from each leaf was divided by total leaf surface area to give the mass of kaolin deposited per square centimeter.

Twenty 7-mm-diameter ($\pm$0.5-mm) squares were dipped twice in the kaolin spray mix and air dried at room temperature after each dip. The mass of kaolin deposited on each square was determined after both 4 h and 4 d in the same way as for the leaves.

The cotton variety used throughout the laboratory and cage assays was C-208 (UAP Southwest, Santa Rosa, TX). Greenhouse pots were 7.5 liters in volume and each contained three plants. All cage studies were conducted outdoors from mid-May to early July 2000 at the USDA-ARS Kika de la Garza Subtropical Agricultural Research Center, Hidalgo County, TX.

Kaolin Application to Excised Squares. In the choice assay, two 7-mm-diameter debracted squares dipped in kaolin and two nontreated squares were placed in randomly selected quadrants in 9-cm-diameter petri dishes. One gravid female boll weevil was released into each petri dish and observed at 10-min intervals for the first 90 min, then at 2.5, 3.5, 4.5, 5.5, and 24 h after the assay was initiated. The position of each boll weevil at each sampling time was recorded as being on a kaolin-dipped square, a nontreated square, or not on a square. Gravid female boll weevils were obtained by placing 30 pairs of field-captured adult boll weevils in 0.5-m^3 cages with 20 fresh squares provided daily for six consecutive days. A sample of five randomly selected females was dissected from each cage to confirm the presence of chorionated eggs; if eggs were present in all five females, the female population in the cage was assumed to be gravid. In both the no-choice and the choice assays, 10 separate petri dishes constituted each of 16 replications. Feeding and oviposition damage to the squares after 24 h were assessed using 100 replications (each petri dish was a replicate). In the no-choice assay, conditions were the same except there were either two kaolin-dipped or two nontreated squares in each petri dish and feeding and oviposition damage to the squares after 24 h were assessed using 185 replications (each petri dish was a replicate). The repeated measures analysis was run to assess the effects of treatment and time on the numbers of boll weevils on the squares in the choice and no-choice assays. Insect numbers were $\log(x + 1)$-transformed before repeated measures analyses; however, untransformed means are presented. The two-sample *t*-test and Yates corrected chi-square test were used to detect treatments effects for the 24-h feeding and oviposition damage in the no-choice and the choice assays, respectively (Analytical Software 1998).

First Contact with Treated or Nontreated Excised Squares. One gravid female boll weevil was released in a 14.5-cm-diameter petri dish for 5 min. One debracted 7-mm-diameter excised cotton square was dipped in kaolin solution, dried, and placed in the petri dish along with a debracted nontreated control square such that the two squares were 10 cm apart from one another and the boll weevil was equidistant from both squares. The square that was first contacted by placement of the boll weevil's tarsi or antennae on the square was recorded. Each of the 15 replications was composed of 10 petri dishes. Two-by-two table test and Yates' corrected chi-square were used to detect treatment differences.

Kaolin Application to Foliage on Whole Cotton Plants, Square Damage. In a choice assay, 30 greenhouse pots of 7-mm-square diameter cotton plants were sprayed with kaolin using a Greenlawn manual pump sprayer. Because they are shielded by bracts, squares received partial or no coverage, which is representative of field conditions when kaolin is applied. One pot of treated cotton plants and one pot of nontreated cotton plants were placed together in a 1 by 0.65 by 1-m cage. Five pairs of boll weevils were released in each cage. Fifteen randomly selected squares from each pot of cotton plants were examined for oviposition punctures after 2, 24, and 72 h, and 1 wk after weevil introduction. Repeated measures analysis was run to assess the effects of treatment and time on the numbers of oviposition damaged squares in the choice and no-choice assays. Numbers of oviposition damaged squares numbers were $\log(x + 1)$-transformed before repeated measures analyses; however, untransformed means are presented (Analytical Software 1998).

Kaolin Application to Foliage on Whole Cotton Plants, Foliar Damage. In a choice assay, pots of cotton plants with all squares removed were sprayed with kaolin, and 30 pots of cotton plants with all squares removed were not treated. One pot of each treatment was paired and placed in 1 by 0.65 by 1-m cages. Twenty-five boll weevils were released in each cage. After 7 d, the extent of damage to petioles and leaves were recorded. Yates' corrected chi-square test was used to compare mean (n = 30) damage (Analytical Software 1998).

In a no-choice assay, 60 pots of cotton plants were sprayed with kaolin, and 60 pots of cotton plants were not treated. Two pots of the same treatment were placed in the cages, 25 boll weevils were released into each cage, and petiole and leaf perforation damage were recorded after 7 d. The two sample *t*-test was used to compare mean (n = 30) damage (Analytical Software 1998).

Small Plot Trials. Twenty-four plots, each 8.1 m wide (8 rows, row spacing = 1 m) by 15.2 m long (0.0125 ha) with a 1-m bare ground buffer between plots were arranged in a completely randomized design at the Kika de la Garza Subtropical Agricultural Research Center, 'Deltapine-50' cotton was planted in 101.6 cm rows on 6 March 2000, and on 12 March 2001. Pendimethalin (Prowl 3.3 EC, American Cyanamid, Parsippany, NJ) at 924 g (AI)/ha was applied by tractor immediately after planting, and weed control was thereafter conducted with a rolling cultivator and by hand-roguing. Irrigation occurred at the start of bloom (mid-May). Beginning 11 April 2000, and 17 April 2001, when the cotton plants had reached pinhead square stage, kaolin solution was applied by tractor-mounted boom sprayer using 18 Teejet 8003E nozzles 1 m apart (each nozzle ≈30 cm directly over the top of a row) at 42.3 liter/ha, 3.5 kg/cm^2. Treatments were reapplied weekly to eight plots and biweekly (once every 2 wk) to eight plots until 21 June 2000, and 25 June 2001. Each application consisted of two passes by the tractor to maximize coverage. Three weeks after the first application in each year, two 47-cm drop nozzles accompanied each boom nozzle. The remaining eight plots were not treated (kaolin-free). No insecticides were applied to any of the small plots. Kaolin particle retention on cotton leaves at 4 h, 1 wk, and 2 wk after the first application in 2000 was measured as previously described using randomly selected fully expanded leaves collected from the biweekly treated plots only.

An adjacent 'Deltapine-50' cotton field planted on the same date as the small plot field, being used for another study on the efficacy of preemptive boll weevil sprays (Heilman et al. 1979), was located <15 m east of the small plot field, was used as a comparison for yield. One-half of the field, a 36 by 150-m plot, received two preemptive azinphosmethyl (Guthion 2 liter, Bayer, Kansas City, MO) at 140.8 g (AI)/ha at pinhead square stage (early May) and 5 d later. The insecticide was applied through 16 Teejet 8003E nozzles, two angled toward each row, at a pressure of 3.5 kg/cm^3 (1.6 liters/min/nozzle) on a tractor boom. The other half of the adjacent field was not treated with any insecticides or kaolin over the course of the entire growing season. Weed control in the adjacent field was conducted as in the small plot field trial.

In the small plot field trial, boll weevil oviposition puncturing was assessed by examining 50 randomly selected squares per plot each week from 5 May to 2 June 2000, and from 11 May to 8 June 2001. In the two adjacent plots, 25 randomly selected squares from each plot quadrant were examined for oviposition punctures weekly from 8 May to 6 June 2000, and from 10 May to 7 June 2001.

Numbers of squares and bolls in 7.6 m of row in each small plot were counted on 19 May 2000, and 25 May 2001, and numbers of bolls were counted again on 9 June 2000, and 18 June 2001. On 26 June 2000 and 29 June 2001, heights of 25 randomly selected cotton plants in each small plot were recorded. The small plots and adjacent plots were defoliated on 7 July 2000 and 11 July 2001 with S, S, S-tributylphosphorotrithioate at 1.6 kg (AI)/ha. Cotton was hand harvested from two 4-m lengths of row in each small plot, and from eight 4-m lengths of row in each adjacent plot on 14 July 2000, and 23 July 2001. Seed cotton and ginned lint weights were recorded.

Treatment differences between means for small plot cotton growth measurements and yields were detected using one-way analysis of variance (ANOVA) for each year and Tukey's honestly significant difference (HSD) to separate the means. The repeated measures analysis was run to assess the effects of treatment and time on the mean numbers of boll weevil damaged squares. Damage was $\log(x + 1)$-transformed before repeated measures analyses; however, untransformed means are presented (Analytical Software 1998). Variations in numbers of damaged squares and in yields in the small plot field versus the adjacent field were not statistically analyzed for significant treatment effects because comparison of the small plots to the large plots did not involve true replication. However, means ± SE are presented.

Results

Mean particle densities on the caged cotton plant leaves were 375.4 ± 18.9 and 368.4 ± 19.3 μg/cm^2 leaf surface area after 4 h and 4 d, respectively. Mean particle densities were 145.0 ± 20.8 and 138.6 ± 20.3 μg on 7-mm-diameter squares kept in petri dishes 4 h and 4 d after application, respectively.

Kaolin Application to Excised Squares, Choice and No-choice Assays. Repeated measures analysis of the choice assay indicated that boll weevils were positioned on nontreated squares more than on kaolin-treated squares (F = 201.98; df = 1, 420; P < 0.0001). Fig. 1 shows that from 0 to 150 min, the mean numbers of weevils positioned on nontreated squares were substantially greater than on the kaolin-treated squares, but at 210 and 270 min, the differences were not significant. At 330 min, the mean number of weevils on kaolin-treated squares was higher than on nontreated squares. The effect of time was significant (F = 4.32; df = 13, 420; P < 0.0001), but only between the first sampling time and all of the other times. A significant interaction between treatment and time (F = 11.55; df = 13, 420; P < 0.0001) was detected. After 24 h, the mean numbers of egg punctures on treated and control squares were similar (Table 1). Also, the mean numbers of squares that contained no eggs and the mean numbers with feeding punctures were not significantly affected by the kaolin particle film (Table 1).

In the no-choice assay, the repeated measures analyses showed that significantly more weevils were lo-

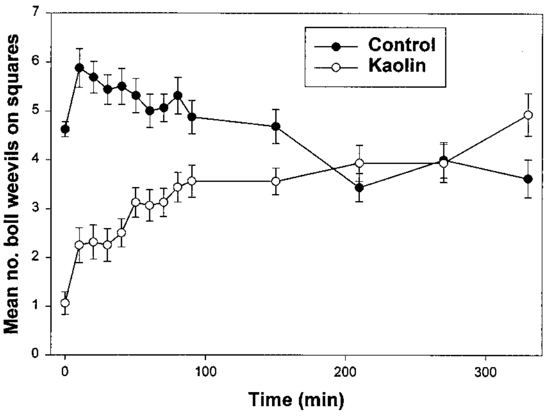

Fig. 1. Mean numbers of boll weevils (±SE) positioned on excised kaolin-treated or nontreated cotton squares, choice assay (n = 16).

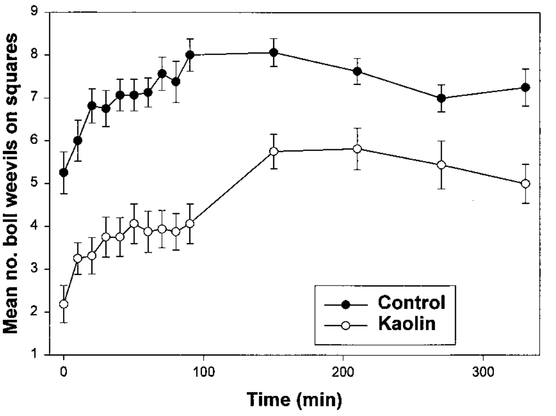

Fig. 2. Mean numbers of boll weevils (±SE) positioned on excised kaolin-treated or nontreated cotton squares, no-choice assay (n = 16).

cated on control squares (F = 246.24; df = 1, 420; $P <$ 0.0001) than on kaolin-treated squares (Fig. 2). The effect of time was significant (F = 5.753; df = 13, 420; $P < 0.0001$); the lowest mean number of boll weevils occurred on the first sampling time. No interaction between treatment and time was detected. After 24 h, control squares had 1.6 times more egg punctures than kaolin-treated squares (Table 1). Completely non-damaged kaolin-treated squares were not significantly more abundant than corresponding controls.

First Contact with Treated or Nontreated Excised Squares. Gravid female boll weevils first contacted kaolin treated excised squares 45.4% less than non-treated squares (χ^2 = 6.01; df = 1, 14; P = 0.0142).

Kaolin Application to Foliage on Whole Cotton Plants, Square Damage. The repeated measures analysis detected a significant treatment effect on mean numbers of oviposition-damaged squares (F = 38.23; df = 1, 232; $P < 0.0001$) but differences steadily decreased until they were no longer apparent after 1 wk (Fig. 3). The effect of time was significant (F = 1040.23; df = 3, 232; $P < 0.0001$); at each consecutive sampling time, the mean number of oviposition-damaged squares increased. A significant interaction was detected between treatment and time (F = 4.48; df = 3, 232; P = 0.004).

Kaolin Application to Foliage on Whole Cotton Plants, Foliar Damage. In the choice assay, the mean number of blackened petioles with wilted or abscised leaves on each pot of kaolin-treated plants (4.6 ± 0.6) was reduced in comparison to the control (14.3 ± 0.9) (χ^2 = 79.59; df = 2, 29; $P < 0.0001$). More perforated leaves were observed on the control plants (4.7 ± 0.4) than in the kaolin sprayed plants (2.4 ± 0.3) (χ^2 = 10.09; df = 1, 29; P = 0.002). Of the perforated leaves, ≈95% lost ≤10% of their area.

In the no-choice assay, the mean number of damaged petioles per pot of kaolin treated cotton plants (3.2 ± 0.3) was significantly lower than that of the control (18.9 ± 0.8) (t = 16.7; df = 1, 28; $P < 0.0001$). A significantly higher mean number of perforated leaves were found on the control plants (5.5 ± 0.4) than on the kaolin-treated plants in each pot (1.2 ± 0.2) (t = 9.29; df = 1, 28; $P < 0.0001$). All of the perforated leaves had lost ≤10% of their areas.

Small Plot Trials. Mean particle density on leaves 4 h after application was 360.0 ± 18.7 μg kaolin per square centimeter of leaf surface. After 1 and 2 wk in the field without rain, particle densities were 319.9 ± 20.8 and 201.0 ± 13.2 μg/cm^2, respectively.

Based on the 50 squares examined in each plot, the repeated measures analyses revealed that treatments (df = 2, 105) had significant effects in both years (2000, F = 18.89, $P < 0.0001$; 2001, F = 38.29, $P <$ 0.0001) on the numbers of boll weevil oviposition-damaged squares. Fig. 4 shows that, in 2000, fewer squares were damaged in the samples from the kaolin-

Table 1. Mean ± SE boll weevil damage to excised cotton squares in Petri dishes in choice and no-choice assays after 24 h

Assay[a]	Treatment	No. egg punctures	No. squares without eggs	No. feeding punctures
Choice	Control	2.93 ± 0.23	0.52 ± 0.07	4.28 ± 0.57
	Kaolin	2.93 ± 0.22	0.65 ± 0.08	4.16 ± 0.51
χ^2		0	0.06	0.06
P		1.0	0.808	0.808
No-choice	Control	0.70 ± 0.09	1.55 ± 0.06	4.36 ± 0.17
	Kaolin	0.44 ± 0.08	1.74 ± 0.04	3.07 ± 0.16
t		2.21	2.56	5.21
P		0.038	0.011	<0.0001

[a] Choice assay 1 df, n = 100; no-choice assay df = 1, 184.

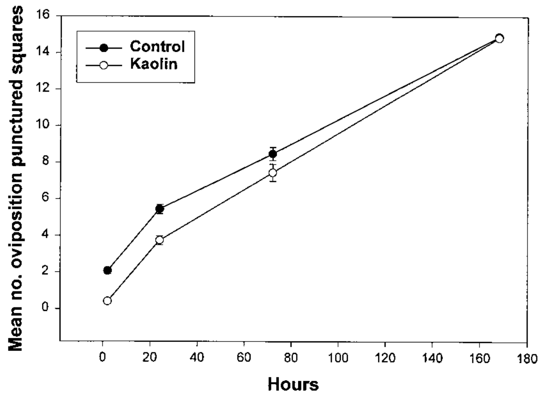

Fig. 3. Mean numbers of squares oviposition punctured (±SE) by boll weevils on cotton plants sprayed with kaolin, choice cage assay (n = 30).

treated plots than from the kaolin-free small plots except for the samples taken on 26 May. Heavy rain washed the kaolin off the cotton foliage on 20 May, and because of muddy field conditions, the next application of kaolin occurred 5 d later. On the last sampling date in 2000, more oviposition-punctured squares were found in the kaolin-free plots and in the biweekly treated plots which did not receive another kaolin application until 7 June. In 2001, samples taken in the weekly treated plots had less damage than the samples from the kaolin-free plots throughout the sampling period (Fig. 4). Oviposition damage in the samples from the biweekly treated plots was roughly intermediate between the kaolin-free samples and the samples from the weekly treated plots on the last three sampling dates.

The effect of time (df = 4, 105) was significant in both years (2000, P < 0.0001, F = 91.65; 2001, P <

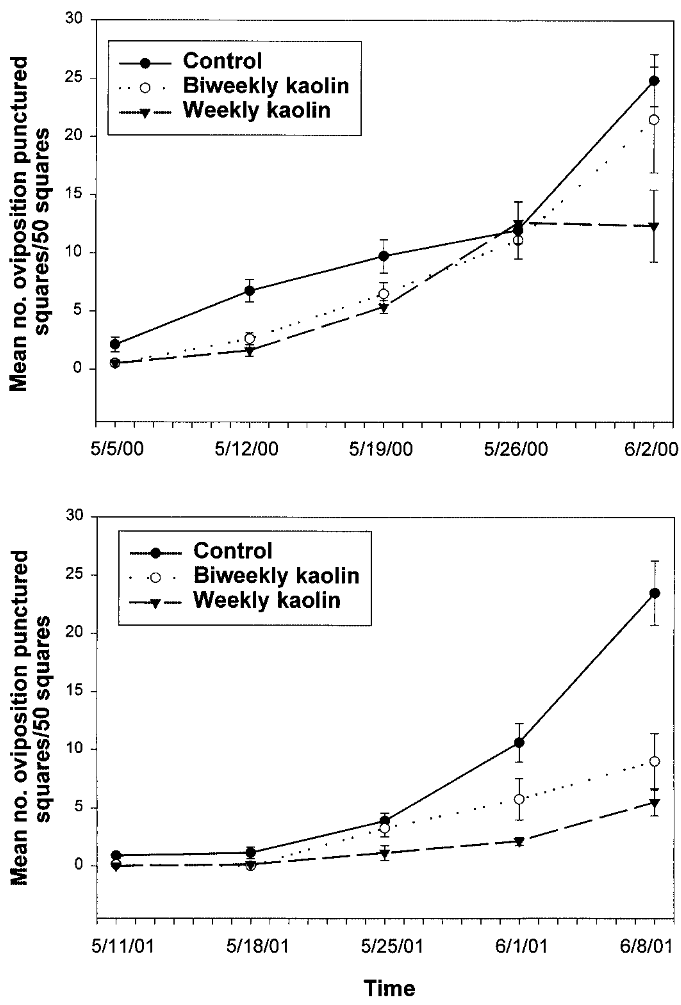

Fig. 4. Mean numbers of squares damaged (±SE) by boll weevils in a small plot field test, Hidalgo County, TX, 2000 and 2001.

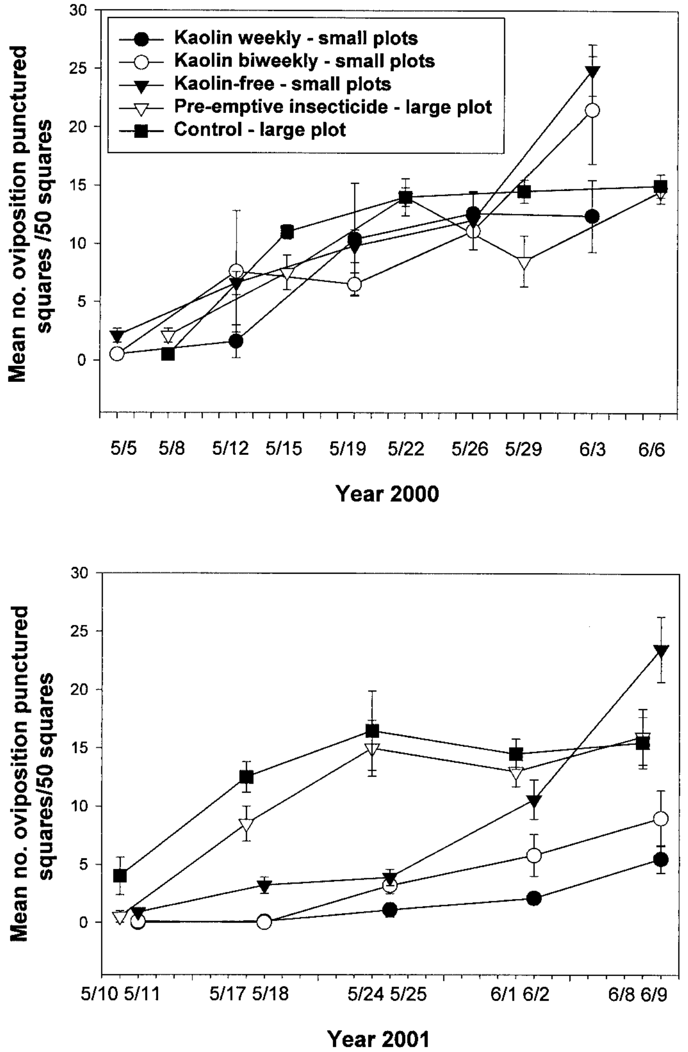

Fig. 5. Mean numbers of squares damaged (±SE) by boll weevils in a small plot field and in an unreplicated adjacent plot that received two preemptive azinphosmethyl applications only, and in another unreplicated adjacent large plot field that was untreated with kaolin and insecticides.

0.0001, $F = 87.45$). Oviposition damage on each successive weekly sampling date increased, except between the first two dates in 2001. Significant interactions were detected between treatment and time (df = 8, 105) in both years (2000, $F = 2.30$, $P = 0.026$; 2001, $F = 2.28$, $P = 0.027$).

Mean numbers of oviposition-punctured squares appeared to be significantly more abundant in the adjacent control plot than in the weekly treated kaolin small plots during 3 of the 5 wk of sampling in 2000 (Fig. 5). There also appeared to be more punctured squares per sample in the adjacent control plot than in the biweekly treated kaolin plots and in the kaolin-free small plots during one and two of the weeks of sampling, respectively. More punctured squares also seem to have been found in the kaolin-free small plots than in the azinphosmethyl-treated adjacent plot during one sampling date. In 2001, there appeared to be lower mean numbers of punctures in each of the samples examined in the treated small plots, including the kaolin-free plots, as compared with the adjacent control plot on all five 2-d sampling times, and as compared with the preemptive azinphosmethyl-treated adjacent plot on the last four of the five 2-d sampling times (Fig. 5). The kaolin-free small plot samples appeared to have fewer mean numbers of punctured squares than the azinphosmethyl-treated adjacent plot on the second and third 2-d sampling times, but more punctured squares than the same adjacent plot on the last 2-d sampling time (Fig. 5).

During both years, no plant growth variables were significantly ($P > 0.05$) affected by kaolin treatment, except for cotton lint yield in 2001 when the kaolin-free plots yielded 18% less lint than the kaolin-treated

Table 2. Mean ± SE cotton plant heights, fruiting structures, and lint yields in kaolin-treated and check plots

Year	Treatment	Plant h, cm	Fruiting structures				Yield cotton lint (kg/ha)
			No. squares	No. blossoms	No. bolls	No. bolls	
2000	Control	67.8 ± 2.0	148.1 ± 20.6	74.9 ± 12.6	179.0 ± 25.9	299.9 ± 12.8	515.3 ± 25.0
	Kaolin biweekly	68.1 ± 3.0	161.5 ± 21.8	81.6 ± 9.3	169.8 ± 21.8	279.5 ± 17.4	507.0 ± 28.2
	Kaolin weekly	62.3 ± 1.9	165.4 ± 24.0	102.4 ± 23.7	182.1 ± 18.1	317.0 ± 9.9	520.5 ± 18.4
2001	Control	77.9 ± 1.7	366.2 ± 54.6	95.5 ± 14.8	152.1 ± 33.6	335.5 ± 19.0	484.3 ± 29.1b
	Kaolin biweekly	73.0 ± 2.1	474.2 ± 51.4	102.8 ± 13.9	127.6 ± 22.9	327.9 ± 27.4	520.6 ± 26.3ab
	Kaolin weekly	76.7 ± 2.7	427.6 ± 27.8	102.2 ± 16.6	160.2 ± 26.1	397.0 ± 37.7	593.5 ± 35.0a

Means followed by different letters within each column and each year are significantly different ($P \leq 0.05$, one-way ANOVA, Tukeys HSD).

plots ($F = 3.36$; df = 2, 21; $P = 0.05$) (Table 2). The azinphosmethyl-treated large plot appeared to yield less lint in 2000 and 2001 (376.0 ± 22.3 kg/ha and 378.6 ± 36.0 kg/ha, respectively) than any of the small plot treatments. The large plot control had the lowest lint yields (2000, 220.6 ± 13.8 kg/ha; 2001, 317.0 ± 24.1 kg/ha).

Discussion

The excised square assays demonstrated that gravid boll weevils prefer to oviposit on squares without kaolin. Because gravid boll weevils tended to move first to nontreated squares without physically contacting the kaolin-treated squares, it appears that boll weevils prefer nontreated squares based, at least to some extent, on differences in the color of the square. However, this visual effect did not completely deter boll weevils from contacting, feeding, and ovipositing on kaolin treated squares.

The excised square choice assay and the cage choice assay for square damage showed that with an increasingly limited supply of nontreated squares or nontreated cotton plants, boll weevils used kaolin-treated squares and squares on whole plants sprayed with kaolin as much as nontreated squares and squares on whole plants that were not sprayed with kaolin. This suggests that kaolin is a deterrent, but it loses effectiveness when preferred (nontreated) host plant material is unavailable. Any barrier effect initially imposed by kaolin was eventually overcome by the weevil's need to oviposit.

Although kaolin provided 68 and 83% protection against boll weevil-induced leaf abscission, and 49 and 78% protection against leaf perforation in the choice and no-choice assays, respectively, boll weevils strongly prefer to feed on squares rather than on other parts of the cotton plant (Lloyd et al. 1961). However, in the absence of squares, the attractiveness of foliage alone was reduced when coated with kaolin, especially when nontreated alternatives were available. Although severe leaf damage in field conditions would not normally occur until after the cotton had already lost most of its squares, the foliage-damage cage assays support the laboratory and cage experiments in which kaolin similarly protected squares.

The mean numbers of boll weevil-damaged squares found in the small plots suggest that during the 5 d when the deterrent effect of kaolin was absent following rainfall in 2000, boll weevils made nearly equal use of the squares in all of the plots. Reapplication of kaolin was thereafter associated with a significant decline in square damage only in the weekly treated plots. The loss of the kaolin film on the biweekly treated foliage and 1 wk further delay in reapplication was probably responsible for the lower degree of protection observed. During the 2001 season, rainfall occurred three times in June, but reapplications of kaolin were conducted within 2 d after each rain in all of the kaolin-treated plots. This might explain the lower boll weevil square damage, particularly in the kaolin-treated plots, and it underscores the importance of continuous coverage with kaolin to maintain its effect. In all of the plots, the percentage of oviposition-punctured squares exceeded the 10–15% insecticide treatment threshold widely accepted in Texas, particularly as the growing season progressed.

The lint yields in the kaolin-treated small plots as compared with the insecticide-treated adjacent plot suggests that kaolin might provide protection from boll weevil injury more effectively than two preemptive insecticide applications, a practice commonly used in the Lower Rio Grande Valley of Texas that aims to suppress early season boll weevil populations. The seemingly higher lint yields in the small plots than in the two adjacent plots suggest that color might play a role in boll weevil orientation toward areas with host plants. Because the adjacent large plots were cultivated under the same conditions as the small plot field, natural differences in boll weevil populations within and among the cotton fields were probably minimal. The observed differences in boll weevil oviposition injury to squares in the small versus large plots appear to have resulted from treatment effects. The inability to conduct valid statistical comparisons of the small versus large plot treatments, however, precluded making probabilistic conclusions about the large versus small plot treatment effects.

The similar lint yields of the three small plot treatments shows that some boll weevils arrived in and made use of the small plots in spite of the white and green checkered appearance of the field. The lower oviposition damage and higher yields in the kaolin-free small plots as compared with the adjacent plots, both without kaolin, appears to result from border effects, despite the 1 m wide buffers between the small plots. Such border effects were not apparent in the adjacent plots because of their larger size, and because they were separated from any kaolin treated cotton by 15 m. Kaolin in the small plots did not completely protect squares from boll weevils presumably because cotton plant volatiles (Chang et al. 1987, Grodowitz et al. 1992) and boll weevil aggregation pheromone (Hardee et al. 1969) from weevils already in the plots attract boll weevils from outside the small plots.

Applications of some particle types for suppression of crop injury have been effective against some pests because abrasion of the insect cuticle or structural disruption of the epicuticle induced water loss and subsequent desiccation (Kalmus 1944, Hunt 1947, Ebeling and Wagner 1959, David and Gardiner 1950). The spotted cucumber beetle, *Diabrotica undecimpunctata howardi* Barber (Richardson and Glover 1932), and walnut husk fly, *Rhagioletis completa* Cresson (Boyce 1932), ingested particles that plugged the hindgut and resulted in mortality. In other instances, including pear psylla, potato leafhopper, and root weevil (Glenn et al. 1999, Lapointe 2000), particles that clung to the arthropods' bodies may have disrupted feeding and caused movement away from treated plants. However, white reflective surfaces have also been shown to repel aphids by affecting their host-finding and settling responses (Kennedy et al. 1961, Kring 1962). This study showed that the boll weevil is less inclined to use kaolin-coated host plants for feeding and oviposition before making physical contact with the plant, which suggests that preference is, to some extent, based on visual cues. The deterrent value of kaolin, however, as shown in the petri dish and cage assays, can be completely overcome by the boll weevil if nontreated plants become scarce.

The field data indicate that kaolin particle film might protect cotton squares from boll weevil injury; however, kaolin applications would need to occur weekly because continuous good coverage is important to maintaining its effect. The laboratory assay using excised squares provides evidence that boll weevil orientation behavior might, at least in part, be affected by color of the host plant. Orientation toward cotton fields might also be affected by the color of a field, or parts of a field, such that boll weevils can distinguish between cotton fields or portions of cotton fields.

In the absence of a highly effective sticker, kaolin particle film must be applied repeatedly during the part of the season when cotton yield is most vulnerable to reduction by boll weevils. Although an economic analysis was not conducted, it appears that weekly application of kaolin particle film would probably be undesirable because of associated labor and fuel costs, and because soil compaction from weekly vehicular traffic could result (in this study, each application was actually two applications). However, repeated applications might become necessary even if an effective sticker is found because new, nontreated canopy growth could attract boll weevils.

Further research on kaolin as a protective measure against boll weevil-induced yield losses should attempt to extend the duration of coverage, including during rainfall, and to increase coverage during each application. Field plots should be larger than the ones used in the small plot part of this study to better observe treatment differences in yield by reducing border effects. However, the border effects observed in the small plots suggest that spraying kaolin on parts of field in lieu of entire fields might provide acceptable levels of protection from boll weevils. It is also conceivable that border effects between treated portions of cotton plants and postapplication growth without kaolin on it might compensate to some degree for the relative reduction in treated foliar surface area.

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References Cited

Analytical Software. 1998. Statistix for Windows. Analytical Software, Tallahassee, FL.

Boyce, A. M. 1932. Mortality of *Rhagioletis completa* Cress. through the ingestion of certain solid materials. J. Econ. Entomol. 25: 1053–1059.

Chang, J. F., J. H. Benedict, T. L. Payne, and B. J. Camp. 1987. Attractiveness of cotton volatiles and grandlure to boll weevils in the field, pp. 102–104. *In* Proceedings, Beltwide Cotton Conference. National Cotton Council, Memphis, TN.

David, W.A.L., and B.O.C. Gardiner. 1950. Factors influencing the action of dust insecticides. Bull. Entomol. Res. 41: 1–61.

Ebeling, W., and R. E. Wagner. 1959. Rapid desiccation of drywood termites with inert sorptive dusts and other substances. J. Econ. Entomol. 52: 190–207.

Glenn, D. M., G. J. Puterka, T. Vanderzwet, R. E. Byers, and C. Feldman. 1999. Hydrophobic particle films: a new paradigm for suppression of arthropod pests and plant diseases. J. Econ. Entomol. 92: 759–771.

Grodowitz, M. J., E. P. Lloyd, and G. H. McKibben. 1992. Comparison of feeding and olfactory behaviors between laboratory-reared and overwintered native boll weevils (Coleoptera: Curculionidae). J. Econ. Entomol. 85: 2201–2210.

Harben, P. W. 1995. The industrial minerals handbook II: a guide to markets, specifications, and prices. Arby Industrial Minerals Division Metal Bulletin. PLC, London.

Hardee, D. D., W. H. Cross, and E. B. Mitchell. 1969. Male boll weevils are more attractive than cotton plants to boll weevils. J. Econ. Entomol. 62: 165–169.

Heilman, M. D., L. N. Namken, J. W. Norman, and M. J. Lukefahr. 1979. Evaluation of an integrated short-season management production system for cotton. J. Econ. Entomol. 72: 896–900.

Hunt, C. R. 1947. Toxicity of insecticide dust diluents and carriers to larvae of the Mexican bean beetle. J. Econ. Entomol. 40: 215–219.

Kalmus, H. 1944. Action of inert dusts on insects. Science 153: 714–715.

Kennedy, J. S., C. O. Booth, and W.J.S. Kerhaw. 1961. Host finding by aphids in the field. III. Visual attraction. Ann. Appl. Biol. 49: 1–21.

Knight, A. L., T. R. Unruh, B. A. Christianson, G. J. Puterka, and D. M. Glenn. 2000. Effects of kaolin-based particle films on obliquebanded leafroller, *Choristoneura rosaceana* (Harris) (Lepidoptera: Tortricidae). J. Econ. Entomol. 93: 744–749.

Kring, J. B. 1962. Reaction of aphids to reflected light. Bull. Entomol. Soc. Am. 8: 159.

Lapointe, S. L. 2000. Particle film deters oviposition by *Diaprepes abbreviatus* (Coleoptera: Curculionidae). J. Econ. Entomol. 93: 1459–1463.

Lloyd, E. P., J. L. McMeans, and M. E. Merkl. 1961. Preferred feeding and egg laying sites of the boll weevil and the effect of weevil damage on the cotton plant. J. Econ. Entomol. 54: 979–984.

Loera-Gallardo, J., D. A. Wolfenbarger, and J. W. Norman, Jr. 1997. Toxicity of azinphosmethyl, methyl parathion, and oxamyl against boll weevil (Coleoptera: Curculionidae) in Texas, Mexico, and Guatemala. J. Agric. Entomol. 14: 355–361.

Miles, D. H., V. Chittawong, P. A. Hedin, and U. Kokpol. 1993. Potential agrochemicals from leaves of *Wedelia biflora.* Phytochem. 32: 1427–1429.

Miles, D. H., K. Tunsugian, V. Chittawong, P. A. Hedin, and U. Kokpol. 1994. Boll weevil antifeedants from *Eleocharis dulcis* Trin. J. Agric. Food Chem. 42: 1561–1562.

Moore, L. and T. F. Watson. 1990. Trap crop effectiveness in community boll weevil (Coleoptera: Curculiondiae) control program. J. Entomol. Sci. 25: 519–525.

Morales-Ramos, J. A., and E. G. King. 1991. Evolution of *Catolaccus grandis* (Burks) as a biological control agent against the cotton boll weevil, p. 724. *In* Proceedings, Beltwide Cotton Conference. National Cotton Council, Memphis, TN.

Page, L. M., D. R. Johnson, M. P. Moret, and S. R. Amaden. 1999. Summary of insecticide performance for boll weevil (*Anthonomus grandis*) control in Arkansas cotton, p. 1168–1169. *In* Proceedings, Beltwide Cotton Conference. National Cotton Council, Memphis, TN.

Puterka, G. J., D. M. Glenn, D. G. Sekutowski, T. R. Unruh, and S. K. Jones. 2000. Progress toward liquid formulations of particle films for insect and disease control in pear. Environ. Entomol. 29: 329–339.

Richardson, C. H., and L. H. Glover. 1932. Some effects of certain "inert" and toxic substances upon the 12-spotted cucumber beetle, *D. duodecempunctata* (Fab.). J. Econ. Entomol. 25: 1176–1181.

Showler, A. T. 2001. Effect of kaolin particle film on boll weevil feeding and oviposition on cotton squares, pp. 942–947. *In* Proceedings, Beltwide Cotton Conference. National Cotton Council, Memphis, TN.

Showler, A. T. 2002. Effects of water deficit stress, shade, weed competition, and kaolin particle film on selected foliar free amino acid accumulations in cotton, *Gossypium hirsutum* L. J. Chem. Ecol. 28: 615–635.

Sterling, W. L. 1978. Fortuitous biological suppression of the boll weevil by the red imported fire ant. Environ. Entomol. 7: 564–568.

Sturm, M. M., W. L. Sterling, and A. W. Hartstack. 1990. Role of natural mortality in boll weevil (Coleoptera: Curculionidae) management programs. J. Econ. Entomol. 83: 1–7.

Summy, K. R., S. M. Greenberg, and J. A. Morales-Ramos. 1997a. Patterns of host utilization by *Catolaccus grandis,* an exotic parasite of boll weevil: effects of host stage. Southwest. Entomol. 22: 337–343.

Summy, K. R., S. M. Greenberg, J. A. Morales-Ramos, and E. G. King. 1997b. Suppression of boll weevil infestations (Coleoptera: Curculionidae) occurring on fallow-season cotton in southern Texas by augmentative releases of *Catolaccus grandis* (Hymenoptera: Pteromalidae). Biol. Control 9: 209–215.

Unruh, T. R., A. L. Knight, J. Upton, D. M. Glenn, and G. J. Puterka. 2000. Particle films for suppression of the codling moth (*Cydia pomonella* (Lepidoptera: Totricidae) in apple and pear orchards. J. Econ. Entomol. 93: 737–743.

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